



Glacier Bay National Park and Preserve Oceanographic Monitoring Program

2009 Annual Report

Natural Resource Technical Report NPS/SEAN/NRTR—2011/508



ON THE COVER

Sitakaday Narrows is a region of strong tidal mixing in lower Glacier Bay.
NPS photo

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Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

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Abstract

The Southeast Alaska Inventory and Monitoring Network took over long-term oceanographic monitoring for Glacier Bay in 2009. It was the 17th consecutive year in that dataset, and this is the first annual report; subsequent updated reports will be generated annually. As operational conditions allowed, vertical profiles of temperature, salinity, light, turbidity, dissolved oxygen concentration, and an index of primary productivity were obtained for the water column once in early spring and once in mid-summer at 22 permanent stations throughout Glacier Bay; seven of those stations were occupied monthly from March through October. In general, parameters reflected typical ranges and spatial (both horizontal and vertical) and temporal trends expected for a high-latitude tidewater glacial fjord, with strong seasonal signals and strong length-of-fjord gradients along the glacier-to-baymouth transects. The water column was well-mixed in winter and strongly stratified in summer. Primary productivity indicators were quite high, indicating together with physical parameters that strong tidal mixing and/or wind-driven upwelling sustain phytoplankton productivity in surface waters from late spring through fall. Compared to historical data, a cold, salty, and dense water column anomaly below 10-m depth was observed during July at a central bay station. This anomaly matches a pattern seen in other northern Gulf of Alaska coastal waters during the 2006–2009 time period and is interpreted as a response to regional physical forcing originating with dynamics of the Aleutian Low pressure center. Data quality and quantity for 2010 and future years should be enhanced by improved equipment including a dedicated vessel, and operational improvements such as casts that sample closer to the bottom.

Acknowledgments

A program of this technical and logistical complexity is not sustainable without support from many quarters. 2009 was the initial year of monitoring using a field and data management protocol developed by Danielson et al. (2010), and the authors of that document were essential to the development of this report. Similarly, it is important to note that the current protocol was adapted from one developed by Hooge et al. (2003), and to acknowledge the work of those authors and their collaborators in maintaining the extended 1993–2008 time series that makes this dataset so valuable. For assistance with 2009 field data collection I thank B. Johnson, B. Moynahan, E. Gurney, C. Smith, J. Smith, W. Clark, M. Johnson, D. Tallmon, and K. Unertl. Oceanographic data can be collected only when there are vessels and operators available to deploy instruments at stations. The 2009 data were collected during eight cruises that were logistically supported by the Glacier Bay National Park and Preserve (GLBA) Resource Management and Protection Divisions; thanks to vessel operators W. Bredow, B. Eichenlaub, J. Smith, and T. Bruno. Similarly, I thank the GLBA Maintenance Division for ongoing vessel maintenance, and particularly B. McDonough for his assistance in fabricating an effective winch/davit system that is interchangeable among several vessels. Special thanks to B. Johnson for developing routines that automate some data analyses and visualizations. Vertical cross-sections of oceanographic data are generated using the Ocean Data View 4.0 software package (Schlitzer 2010). Reviews by B. Moynahan and S. Danielson resulted in substantial improvements to this report.

Introduction

Oceanography is one of several long-term monitoring “vital signs” identified by the National Park Service (NPS) Southeast Alaska Inventory and Monitoring Network (SEAN) as important in order to be able to continually assess the ecological health of Glacier Bay National Park and Preserve (GLBA; Moynahan et al. 2008). A detailed oceanographic monitoring protocol (Danielson et al. 2010) was developed to standardize data collection, analyses, and reporting. This annual data report documents the first year of data collection following the development of that protocol. Annual reports summarize the field efforts and resulting data of the previous sampling year. The “oceanographic sampling year” begins with a mid-winter cruise in December or January and ends with an October cruise, after which the measurement instrument receives annual service and sensor calibration. Calibration results allow for final data to be certified, and the annual report is typically generated in January or February. The annual report is intended to be a timely release of summarized data, and it includes a narrative description of field activities, unusual or otherwise noteworthy observations, and graphical and tabular data summaries to place the data in historical context. It is succinct and synoptic in nature, and is aimed at a primary audience of GLBA managers, researchers, and interested stakeholders from the public at large. Care has been taken to assure accuracy of raw data values upon which this report is based; a more analytical interpretation of the data is undertaken in a more comprehensive but less frequent trend report (typically issued on a regular five-year basis).

Long-term monitoring of Glacier Bay oceanographic parameters is a key element of informed park management. Glacier Bay’s ocean waters strongly influence ecosystems across the entire GLBA. Together with weather, bathymetry, and glaciers and other terrestrial influences, oceanographic components determine horizontal water movement and vertical stability, thereby driving the spatial and temporal dynamics of energy, and physical, chemical, and biological characteristics of the water column. Marine biological communities and their constituent components—from primary producers to apex predators—are fundamentally controlled in this way. Moreover, because the land/ocean interface is porous to the transfer of energy, materials, and biophysical signals, the Glacier Bay marine system is an important physical and biological driver of adjacent terrestrial systems. Consequently, for park managers to fully understand and protect all park resources, they must start with the waters of Glacier Bay itself. In addition to having a basic knowledge of oceanographic components and processes, it is essential to monitor key parameters that are likely to influence the condition of many specific resources—both marine and terrestrial—throughout the park and region.

The GLBA oceanographic monitoring protocol (Danielson et al. 2010) summarizes the purpose, design, and all methods for long-term oceanographic sampling. Oceanographic measurements collected on hydrographic surveys enable a “bottom-up” perspective of ecological relationships. Physical parameters (measured vertically throughout the water column at multiple locations) include water temperature, salinity, light, turbidity, and dissolved oxygen. These measurements characterize the environment that directly impacts both lower trophic (e.g., phytoplankton) and upper trophic (e.g., crabs, fishes, marine mammals, and birds) organisms through their influence on metabolic rates, ability to support carbon fixation through production of chlorophyll, and/or the propensity for organisms to be retained within or exported from the euphotic layer. Fluorescence measurements of chlorophyll-*a* provide an index of the phytoplankton standing stock, which in turn forms the food base for primary consumers (zooplankton) and the

subsequent cascade of carbon through trophic levels to apex predators (e.g., fishes, marine mammals and birds). Thus, observations made within this monitoring program form a foundation upon which other (e.g., habitat, population) aspects of the marine ecosystem within Glacier Bay can be evaluated.

Since 1993, the NPS and the U.S. Geological Survey (USGS) have monitored oceanographic conditions at 24 standard stations distributed throughout Glacier Bay. Select oceanographic parameters have been measured during periodic visits to those stations each year. The core suite of CTD (Conductivity-Temperature-Depth) vertical profile measurements has been supplemented with additional measurements of turbidity, photosynthetically-active radiation (PAR), and chlorophyll-*a* concentration. The entire long-term dataset, along with annual reports, peer review publications, and program evaluations are available from the SEAN oceanography webpage (http://science.nature.nps.gov/im/units/sean/OC_Main.aspx). In 2009, SEAN developed the current revised protocol (also available on the SEAN webpage), largely based on a previous USGS protocol (Hooge et al. 2003).

The objectives for the GLBA oceanographic monitoring program (Danielson et al. 2010) are to:

- 1) Provide a dataset on physical oceanographic conditions in Glacier Bay (water temperature, salinity, stratification, PAR, and turbidity [optical backscatterance, OBS]) that can be used to better understand seasonal and interannual changes in the estuarine dynamics of Glacier Bay and the greater Southeast Alaska oceanographic system.
- 2) Provide a baseline oceanographic dataset (water temperature, salinity, stratification, PAR, OBS, dissolved oxygen, and chlorophyll-*a* fluorescence) that can be used by biologists to understand spatial and temporal variation in the abundance patterns of a variety of organisms including phytoplankton, zooplankton, marine invertebrates, fishes, marine mammals, and seabirds of Glacier Bay.

Methods

Nine times each year we measure a suite of oceanographic water column parameters at permanent sampling “stations” located mid-channel throughout Glacier Bay (Figure 1). There are 22 standard oceanographic stations, including two just outside the fjord mouth that provide additional information about the water flowing in and out of Glacier Bay proper. Seven stations are sampled monthly from March through October to describe seasonal variation during times of the strongest physical structure and highest productivity. These are called the “core stations.” Twice a year, in July (mid-summer) and December/January (mid-winter), we sample the core stations and the remaining 15 stations to detect annual or longer signals. This design achieves a balance between intensive temporal sampling to resolve seasonal signals, and intensive spatial sampling to resolve annual signals and reveal long-term trends.

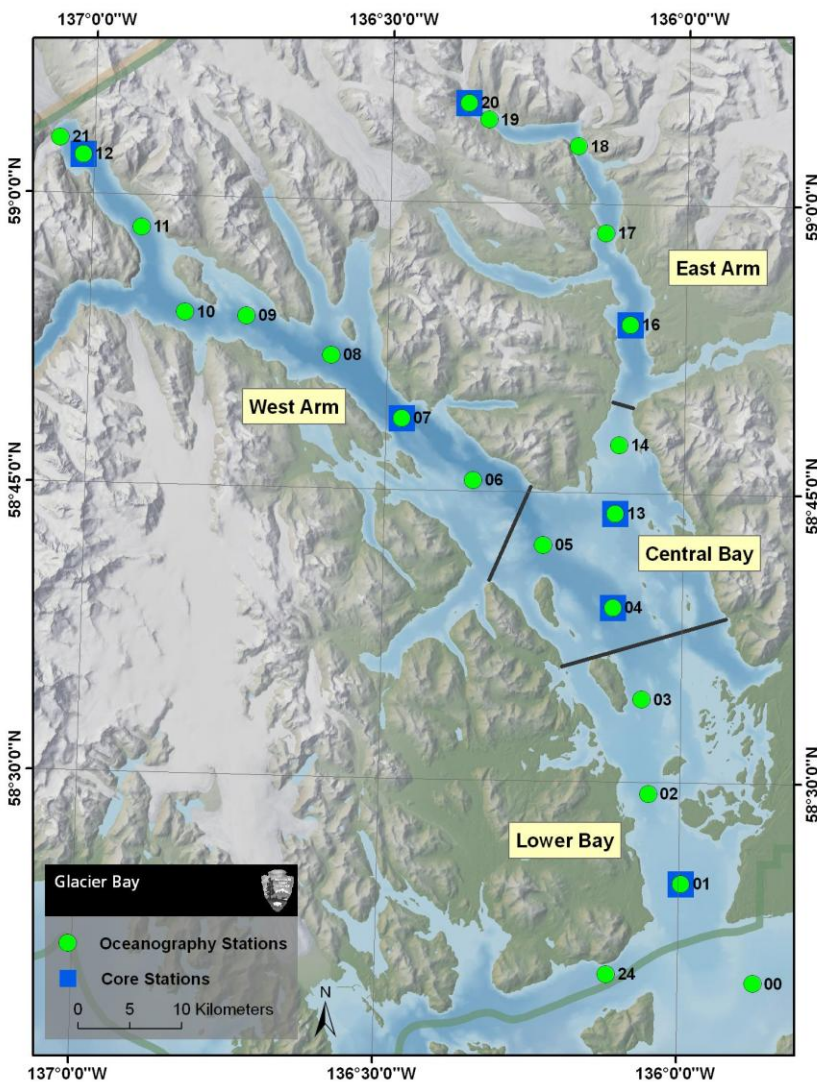


Figure 1. Oceanographic sampling stations in Glacier Bay. Shaded bathymetry indicates relative water depth (darker means deeper). Station depths range from 53 m (Station 00) to 435 m (Station 07).

Measurements are captured by an array of sensors mounted together in an instrument cluster called a CTD (Figure 2) which is lowered through the water column (“cast”) at a rate of ~ 1 m/sec from the surface to just above the bottom. Parameters are measured twice per second, and the data from each cast are stored within the CTD and downloaded at the end of the survey. Together the measurements yield a vertical profile of important water column characteristics for each station location.



Figure 2. The CTD ready to be deployed at an oceanographic station.

Parameters (and their units of measure) include water temperature ($^{\circ}\text{C}$), salinity (Practical Salinity Units or PSUs), PAR ($\mu\text{E}/\text{cm}^2 \cdot \text{sec}$), chlorophyll-*a* fluorescence (an index of chlorophyll concentration and thus phytoplankton standing stock or primary production, in mg/m^3), OBS (turbidity, in Nephelometric Turbidity Units or NTUs), and dissolved oxygen concentration (ml/L - starting with the June 2009 survey). A strain gauge continuously records water pressure which is converted to depth in meters. Measurements of temperature and salinity are subsequently analyzed together to calculate density ($\sigma\text{-t}$, kg/m^3) and vertical density gradient ($\text{kg}/\text{m}^3/\text{m} = \text{kg}/\text{m}^4$, a measure of the rate of change in density with depth which describes stratification relative intensity and indicates the vertical location of the pycnocline). Raw data for all parameters are processed and verified following each sampling survey (referred to as a “cruise”). Detailed field data collection and data processing/management methods are documented in the SEAN oceanography monitoring protocol (Danielson et al. 2010).

Results

Coverage

Table 1 shows the sampling coverage across the 2009 cruise year. The 2009 cruise year did not include a mid-winter cruise (Dec. 2008–Jan. 2009) because no vessel/operator was available. Normally the mid-winter cruise would be an “all-stations” cruise. We decided to capture as many of those stations as possible (indicated by * in the March column of Table 1) during the March cruise (normally a “core-stations” cruise), on the assumption that the early spring date would somewhat approximate the “winter” oceanographic condition. Nineteen of 22 stations were occupied during the March cruise; Stations 12 and 21 (extreme upper Tarr Inlet) and 20 (extreme upper Muir Inlet) were inaccessible due to the presence of non-navigable surface pan ice. Unfortunately, cast data from Stations 00, 01, 02, and 03 were lost on that March cruise because the CTD internal memory was exceeded. During the April cruise (normally a “core-stations” cruise), Stations 02, 03, and 11 (indicated by * in the April column) were also occupied. Stations 02 and 03 were sampled because it was convenient and it was thought that end users might value the additional lower-bay data since it was missing from the March cruise; Station 11 was sampled because adjacent core Station 12 (extreme upper Tarr Inlet) was again inaccessible due to the presence of non-navigable pan ice. Per the modified sampling design of the new SEAN protocol, Station 24 (Cross Sound) was established and first occupied during the mid-July cruise.

Table 1. Sampling coverage of oceanographic stations during the 2009 cruise year. **Red** identifies the seven “core stations” (01, 04, 07, 12, 13, 16, 20). An asterisk indicates non-core station added to spring 2009 cruises.

Station	Mid-winter	March	April	May	June	Mid-July	August	September	October
00						X			
01			X	X	X	X	X	X	X
02			X*			X			
03			X*			X			
04		X	X	X	X	X	X	X	X
05		X*				X			
06		X*				X			
07		X	X	X	X	X	X	X	X
08		X*				X			
09		X*				X			
10		X*				X			
11		X*	X*			X			
12				X	X	X	X	X	X
13		X	X	X	X	X	X	X	X
14		X*				X			
16		X	X	X	X	X	X	X	X
17		X*				X			
18		X*				X			
19		X*				X			
20			X	X	X	X	X	X	X
21						X			
24						X			

Operations

2009 was a successful year for the oceanographic monitoring program, especially given that it was the “hand-off” year of the basic protocol from USGS to NPS/SEAN and the initial year of implementing the newly-revised protocol. Thus, we fully expected that some level of refinement troubleshooting and refinement would be required as the new protocol was evaluated in practice. Unfortunately, completion of the mid-winter survey was precluded by weather. However, we believe the early March “all-stations” survey (normally a “core stations” survey) may reasonably represent the winter condition. As described in the above Coverage section, some stations in the extreme upper inlets remained unreachable in the early spring months because of non-navigable pan ice. In the future some of these stations may continue to be inaccessible from December into April in some years. We established Station 24 on the Cross Sound (west) side of the mouth of Glacier Bay in July; from this point forward, this station will be occupied during the July and mid-winter “all-stations” surveys.

We experienced two cases of single sensor failure, each affecting a single parameter for all casts in a single monthly cruise. These are explained in greater detail below in the Parameters section.

Besides weather and presence of pan ice, suitable vessel and/or operator availability was a challenge in 2009 as has been the case in the past. Because CTD deployment requires a winch and davit, only certain GLBA vessels can be used. Moreover, GLBA policy restricts operation of those vessels to properly certified staff. We are addressing these limitations on multiple fronts in 2010. First, SEAN acquired its own dedicated vessel (to be shared with GLBA where possible) in autumn 2010, and the boat should be in full operation in 2011. Multiple network and GLBA personnel will be certified to operate it. In 2009 SEAN acquired a portable hydraulic winch/davit system, custom-designed to be interchangeable among several GLBA vessels; this system will be based on the new vessel, but it will remain available for use on other vessels. Additionally, in 2010 several SEAN and GLBA personnel will become certified to operate the vessels currently equipped to conduct oceanographic surveys. Collectively, these measures will significantly address issues of vessel and operator availability. Nevertheless, we will likely continue to rely on GLBA Protection Division vessels (often the only vessels remaining in the water during the off-season) to support at least the mid-winter hydrographic surveys.

Several seemingly small but nonetheless important operational improvements were implemented in 2009. The new hydraulic winch/davit system described above made CTD deployments safer and easier than the older, direct-drive capstan arrangement. A few additional upgrades, including changing from poly to nylon line, similarly made the overall operation easier and faster. Several protocol improvements will result in higher-quality data; these include deeper casts as well as greater attention to surface “soak” time (along with associated “surface depth”), and the 1 m/sec vertical downcast rate. A sensor for dissolved oxygen was added to the CTD starting with the June 2009 survey. In 2009 SEAN acquired a new CTD (complete with all sensors) to make it fully redundant with the “old” instrument. Having a backup instrument makes the entire monitoring protocol more robust.

Perhaps the single most significant operational improvement in 2009 was the development and implementation of the revised formal monitoring protocol. Together with the enhanced consistency and continuity of personnel collecting and processing field data, this should result in substantially more and higher quality information.

Parameters

In general, data quality was good, with isolated exceptions. All March cast data from Station 01 were lost when the CTD memory was inadvertently exceeded. Fluorescence data from the March cruise were disqualified for all stations due to an unexplained sensor failure. PAR measurements for the June 2009 survey were similarly disqualified due to compromised data, probably caused by a leaky connector. Rare catastrophic sensor failures notwithstanding, back-to-back casts from Station 13 during the September survey returned virtually identical data, providing confidence in sensor precision. Moreover, post-season calibrations of all sensors indicated high sensor accuracy.

Tables 2 and 3 summarize the oceanographic parameters by core station and survey month. Table 2 shows values averaged over the upper 0–50 m portion of the water column where the majority of primary production, macronutrient utilization, phytoplankton standing stock, thermal stratification, and low-salinity lenses occur, thus providing a broad perspective on the physical, chemical, and phytoplankton components of the system. Table 3 shows values that are generally descriptive of “bottom water”; these values are averaged across 10-m depth bands centered on a depth (for each station) that is well below the pycnocline yet not so deep that data are not consistently captured by casts at that station.

Table 2a. 2009 oceanographic data summary of measured parameters (temperature, salinity, density, and vertical density gradient) at core stations, averaged across the upper 50 m of the water column. “Min” and “max” refer to minimum and maximum data values, respectively; “SD” = standard deviation; n = sample size. Note the absence of standard deviation statistics for vertical density gradient (noisy parameter and dangerous to attempt to read too much into it).

Station	Month	Temperature (°C)					Salinity (PSU)					Density (kg/m ³)					Vertical Density Gradient (kg/m ⁴)			
		Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	n	Max	Depth of max (m)
01	Dec-Jan ¹																			
	Mar ²																			
	Apr	3.99	3.98	4.03	0.01	49	31.54	31.52	31.58	0.02	49	25.03	25.02	25.06	0.01	49	0.00	47	0.00	46
	May-June ³	5.81	5.22	6.38	0.56	95	31.63	31.46	31.96	0.15	95	24.91	24.77	25.10	0.08	95	0.00	91	0.03	30
	Jul	7.18	7.11	7.72	0.13	46	31.79	30.94	31.90	0.20	46	24.87	24.12	24.96	0.17	46	0.02	44	0.17	4
	Aug	7.43	7.21	8.24	0.29	28	31.34	29.20	31.87	0.74	28	24.48	22.69	24.93	0.62	28	0.08	26	0.40	2
	Sep	7.51	7.37	8.64	0.24	50	30.58	28.02	31.50	0.66	50	23.87	21.72	24.61	0.55	50	0.05	57	0.77	3
	Oct	7.25	7.24	7.26	0.00	47	30.23	30.11	30.33	0.05	47	23.63	23.54	23.71	0.04	47	0.00	45	0.01	6
04	Dec-Jan ¹																			
	Mar	3.55	3.48	3.59	0.03	50	30.99	30.89	31.04	0.05	50	24.64	24.57	24.68	0.03	50	0.00	236	0.02	11
	Apr	3.72	3.66	3.78	0.04	48	31.02	30.87	31.19	0.12	48	24.65	24.53	24.79	0.10	48	0.00	265	0.02	35
	May-June ³	5.08	3.76	8.09	1.16	100	31.07	28.72	31.55	0.57	100	24.54	22.33	24.84	0.51	100	0.01	516	0.52	3
	Jul	7.16	6.20	11.44	1.15	50	30.21	21.61	31.19	2.03	50	23.63	16.30	24.52	1.74	50	0.03	257	2.01	3
	Aug	7.57	6.65	9.56	0.76	50	29.93	16.03	31.07	2.58	50	23.35	12.25	24.37	2.09	50	0.05	224	3.80	2
	Sep	7.40	7.16	7.87	0.17	50	29.67	25.79	30.56	1.07	50	23.17	20.07	23.90	0.86	50	0.02	236	0.79	4
	Oct	7.26	6.83	7.42	0.12	50	29.47	25.05	30.49	1.47	50	23.03	19.61	23.84	1.14	50	0.02	249	0.70	6
07	Dec-Jan ¹																			
	Mar	3.58	3.30	3.72	0.13	50	30.96	30.75	31.04	0.08	50	24.61	24.46	24.67	0.06	50	0.00	299	0.04	5
	Apr	3.68	3.53	3.75	0.06	34	31.03	30.83	31.13	0.09	34	24.65	24.52	24.74	0.07	34	0.00	354	0.01	23
	May	4.16	3.70	7.19	0.93	49	30.96	29.33	31.24	0.44	49	24.56	22.93	24.82	0.45	49	0.00	408	0.32	7
	Jun	4.83	3.97	10.28	1.27	50	30.75	23.87	31.25	1.22	50	24.32	18.23	24.80	1.10	50	0.02	254	2.20	2
	Jul	7.03	6.14	11.48	1.17	50	29.83	16.42	31.20	2.85	50	23.34	12.58	24.53	2.36	50	0.03	357	2.74	2
	Aug	7.03	6.55	8.28	0.37	50	29.81	11.07	30.99	3.27	50	23.33	8.51	24.32	2.59	50	0.07	187	6.11	2
	Sep	7.31	7.02	7.78	0.19	50	29.80	19.05	30.73	1.94	50	23.29	14.88	24.05	1.53	50	0.02	333	3.07	2
	Oct	7.34	6.37	7.52	0.23	50	29.55	23.43	30.41	1.50	50	23.09	18.39	23.78	1.16	50	0.02	371	1.09	3
12	Dec-Jan ¹																			
	Mar ⁴																			
	Apr ⁴																			
	May	3.91	3.66	6.33	0.53	50	30.76	24.64	31.23	1.08	50	24.43	19.34	24.82	0.90	50	0.02	260	2.04	2
	Jun	3.88	3.69	4.79	0.29	50	30.55	23.70	31.16	1.36	50	24.26	18.78	24.76	1.10	50	0.02	260	1.66	2
	Jul	5.42	4.02	6.15	0.48	50	29.39	14.21	30.80	3.45	50	23.19	11.28	24.35	2.71	50	0.05	243	2.33	2
	Aug	5.66	4.50	6.38	0.39	49	29.60	20.65	30.47	2.09	49	23.33	16.36	24.04	1.63	49	0.04	215	1.71	4
	Sep	6.64	4.78	7.32	0.48	50	29.27	18.65	30.32	1.99	50	22.95	14.76	23.86	1.55	50	0.03	253	2.50	2
	Oct	6.90	5.07	7.12	0.31	50	29.26	21.44	30.26	1.50	50	22.92	16.94	23.70	1.16	50	0.03	249	2.02	2

Table 2a. 2009 oceanographic data summary of measured parameters (temperature, salinity, density, and vertical density gradient) at core stations, averaged across the upper 50 m of the water column. “Min” and “max” refer to minimum and maximum data values, respectively; “SD” = standard deviation; n = sample size. Note the absence of standard deviation statistics for vertical density gradient (noisy parameter and dangerous to attempt to read too much into it) (continued).

Station	Month	Temperature (°C)					Salinity (PSU)					Density (kg/m ³)					Vertical Density Gradient (kg/m ⁴)			
		Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	n	Max	Depth of max (m)
13	Dec-Jan ¹																			
	Mar	3.74	3.71	3.78	0.02	50	30.93	30.80	31.00	0.05	50	24.58	24.47	24.64	0.04	50	0.00	124	0.02	56
	Apr	3.70	3.68	3.72	0.01	36	31.09	30.97	31.19	0.05	36	24.70	24.61	24.78	0.04	36	0.00	106	0.02	16
	May-June ³	4.69	3.79	8.03	0.82	98	31.15	29.10	31.40	0.37	98	24.65	22.64	24.88	0.36	98	0.01	252	0.55	4
	Jul	7.32	6.31	12.08	1.23	50	30.14	19.53	31.17	2.25	50	23.55	14.60	24.47	1.93	50	0.07	127	2.36	3
	Aug	7.49	6.76	9.00	0.59	50	30.02	23.22	31.04	1.83	50	23.43	17.91	24.33	1.50	50	0.05	117	0.91	2
	Sep	7.31	7.00	7.73	0.17	100	29.97	27.66	30.66	0.82	100	23.42	21.55	24.01	0.66	100	0.02	237	0.27	6
	Oct	7.38	7.24	7.57	0.09	50	29.67	26.44	30.32	0.99	50	23.18	20.65	23.70	0.78	50	0.03	123	0.40	5
16	Dec-Jan ¹																			
	Mar	3.91	3.70	4.01	0.06	50	30.84	30.53	30.91	0.08	50	24.49	24.26	24.55	0.07	50	0.00	295	0.04	2
	Apr	3.74	3.71	3.80	0.03	26	30.95	30.90	30.99	0.03	26	24.59	24.54	24.62	0.03	26	0.00	275	0.01	32
	May-June ³	4.21	3.69	7.61	0.77	100	30.74	26.75	31.20	0.77	100	24.38	20.85	24.77	0.69	100	0.01	557	1.11	2
	Jul	6.72	5.82	9.04	0.71	50	30.03	12.82	31.16	3.14	50	23.54	9.92	24.54	2.52	50	0.05	254	4.71	2
	Aug	7.06	6.34	8.37	0.47	50	29.93	16.45	31.01	2.54	50	23.42	12.73	24.36	2.03	50	0.04	276	3.63	2
	Sep	7.19	6.84	7.41	0.16	50	29.74	21.07	30.55	1.74	50	23.25	16.49	23.93	1.37	50	0.03	276	2.23	2
	Oct	7.19	6.70	7.37	0.20	50	29.33	24.73	30.35	1.39	50	22.94	19.37	23.77	1.08	50	0.02	276	0.70	5
20	Dec-Jan ¹																			
	Mar ⁴																			
	Apr	3.94	3.70	4.74	0.32	49	30.71	29.42	30.98	0.39	49	24.38	23.28	24.62	0.34	49	0.01	154	0.18	5
	May-June ³	4.11	3.67	7.37	0.87	100	30.60	22.33	31.20	1.44	100	24.27	17.42	24.79	1.21	100	0.03	305	1.30	3
	Jul	4.92	1.83	6.26	0.65	50	29.29	5.20	30.83	4.39	50	23.16	4.12	24.42	3.47	50	0.11	154	6.87	2
	Aug	5.58	3.78	6.15	0.47	50	28.86	6.62	30.71	5.20	50	22.75	5.27	24.26	4.09	50	0.12	154	5.31	4
	Sep	6.29	4.88	6.71	0.30	50	29.51	14.96	30.50	2.62	50	23.18	11.84	23.99	2.05	50	0.07	153	3.82	2
	Oct	6.67	5.80	6.89	0.25	50	29.24	21.09	30.40	1.85	50	22.92	16.60	23.88	1.44	50	0.05	154	1.59	2

¹No mid-winter cruise occurred in 2009 because no vessel/operator was available.

²No March data from Station 01 because the CTD internal memory capacity was inadvertently exceeded.

³To avoid conflicting with the June 1–July 15 closure of upper Muir Inlet to motorized access, the “June” sampling date for Stations 01, 04, 13, 16, and 20 actually occurred on May 31; hence, data from the May and June cruises are averaged together for those stations.

⁴Indicates the station was inaccessible due to the presence of pan ice.

Table 2b. 2009 oceanographic data summary of measured parameters (fluorescence, dissolved oxygen, OBS, and PAR) at core stations, averaged across the upper 50 m of the water column. “Min” and “max” refer to minimum and maximum data values, respectively; “SD” = standard deviation; n = sample size. Note the absence of standard deviation statistics for PAR (decreases exponentially from the surface, so standard deviation has little meaning).

Station	Month	Fluorescence (mg/m ³)					Dissolved Oxygen (mg/L)					OBS (NTU)					PAR (μE/cm ² * s)		
		Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max
01	Dec-Jan ¹																		
	Mar ²																		
	Apr	2.93	1.61	3.67	0.42	49						3.09	2.95	3.27	0.07	49	15.69	0.03	206.00
	May-June ³	9.89	2.18	23.29	6.39	95	6.20 ⁵	5.93 ⁵	6.42 ⁵	0.18 ⁵	48 ⁵	10.23	3.12	17.35	6.92	95	6.36 ⁶	0.04 ⁶	96.88 ⁶
	Jul	4.65	3.95	6.94	0.70	46	4.77	4.70	5.33	0.13	46	15.32	15.18	15.52	0.07	46	11.83	0.05	105.62
	Aug	4.26	2.55	5.35	1.00	28	4.45	4.20	5.33	0.33	26	14.93	14.72	15.07	0.09	28	49.07	0.42	263.67
	Sep	3.46	2.00	7.23	1.29	50	4.36	3.96	5.11	0.24	50	16.62	14.35	18.32	1.00	50	1.53	0.03	21.40
	Oct	1.88	1.39	2.19	0.18	47	4.79	4.77	4.80	0.01	44	18.23	17.87	18.92	0.25	47	17.42	0.04	416.31
04	Dec-Jan ¹																		
	Mar											1.44	1.34	1.63	0.07	50	33.70	0.30	234.75
	Apr	4.25	0.82	8.96	2.77	48						1.93	1.86	2.01	0.03	48	12.06	0.06	126.10
	May-June ³	7.87	1.00	57.86	12.53	100	7.05 ⁵	6.51 ⁵	10.34 ⁵	0.84 ⁵	50 ⁵	9.68	1.89	18.52	7.60	100	8.58 ⁶	0.03 ⁶	131.60 ⁶
	Jul	7.97	1.06	55.74	13.19	50	6.29	5.59	9.96	1.26	50	14.96	14.50	17.15	0.68	50	22.19	0.05	349.92
	Aug	10.18	1.09	57.87	15.44	50	5.83	5.14	9.40	1.20	50	14.17	13.71	17.00	0.72	50	43.62	0.05	874.50
	Sep	3.60	1.22	12.66	2.62	50	4.87	4.56	6.02	0.34	50	14.60	13.98	15.70	0.36	50	8.59	0.04	122.51
	Oct	2.27	1.07	6.43	1.37	50	4.95	4.64	6.44	0.47	50	15.41	15.12	15.60	0.15	50	32.19	0.04	621.46
07	Dec-Jan ¹																		
	Mar											1.42	1.28	1.65	0.08	50	26.66	0.17	262.27
	Apr	1.41	0.54	3.48	0.97	34						1.90	1.86	1.97	0.03	34	8.33	0.51	37.43
	May	13.49	1.09	60.03	16.69	49						2.24	1.96	3.08	0.35	49	18.86	0.04	320.47
	Jun ⁷	3.38	0.80	35.90	6.02	50	7.03	6.26	10.12	1.06	50	13.52	13.03	16.06	0.59	50			
	Jul	7.86	0.80	58.00	13.25	50	6.34	5.64	9.66	1.16	50	15.12	14.40	20.14	1.28	50	9.25	0.04	184.97
	Aug	8.23	0.78	54.59	13.47	50	5.88	5.26	10.07	1.15	50	14.11	13.66	18.22	1.09	50	2.16	0.05	48.23
	Sep	2.93	0.75	21.88	4.52	50	4.93	4.67	7.57	0.57	50	14.66	14.28	19.02	0.89	50	12.72	0.04	218.24
	Oct	1.92	0.65	7.50	1.81	50	4.89	4.58	6.93	0.52	50	15.09	14.69	18.15	0.54	50	8.71	0.05	80.59
12	Dec-Jan ¹																		
	Mar ⁴																		
	Apr ⁴																		
	May	8.40	0.65	49.98	12.99	50						3.87	2.42	9.75	1.92	50	5.84	0.03	164.18
	Jun ⁷	3.25	0.59	11.51	2.89	50	6.76	5.98	10.32	1.35	50	19.39	14.86	29.65	3.79	50			
	Jul	1.98	0.95	9.19	1.78	50	6.72	6.26	9.07	0.77	50	83.00	26.95	156.73	18.02	50	1.02	0.03	45.33
	Aug	1.24	0.66	3.59	0.84	49	6.31	6.07	7.90	0.46	49	117.98	57.09	239.97	35.87	49	0.12	0.05	3.78
	Sep	2.10	0.30	16.62	3.66	50	5.70	5.48	7.65	0.40	50	30.64	22.85	45.80	7.88	50	4.72	0.02	190.51
	Oct	1.83	0.39	7.78	2.07	50	5.15	4.96	6.70	0.32	50	17.18	15.32	25.87	1.97	50	3.94	0.03	132.06

Table 2b. 2009 oceanographic data summary of measured parameters (fluorescence, dissolved oxygen, OBS, and PAR) at core stations, averaged across the upper 50 m of the water column. “Min” and “max” refer to minimum and maximum data values, respectively; “SD” = standard deviation; n = sample size. Note the absence of standard deviation statistics for PAR (decreases exponentially from the surface, so standard deviation has little meaning) (continued).

Station	Month	Fluorescence (mg/m ³)					Dissolved Oxygen (mg/L)					OBS (NTU)					PAR (μE/cm ² * s)		
		Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max
13	Dec-Jan ¹																		
	Mar											1.48	1.374	1.713	0.079	50	19.79	0.14	183.65
	Apr	2.16	1.08	4.72	0.99	36						2.02	1.95	2.10	0.04	36	2.76	0.09	17.14
	May-June ³	8.56	0.87	69.25	17.40	98	7.00 ⁵	6.70 ⁵	9.88 ⁵	0.61 ⁵	49 ⁵	8.52	1.87	16.50	6.50	98	1.77 ⁶	0.03 ⁶	44.81 ⁶
	Jul	7.54	1.50	25.16	6.46	50	6.09	5.49	8.05	0.71	50	15.10	14.77	16.62	0.38	50	24.01	0.06	372.75
	Aug	4.65	1.04	13.81	3.68	50	5.53	5.17	7.19	0.55	50	14.12	13.62	16.35	0.83	50	10.53	0.04	171.43
	Sep	2.20	1.02	6.05	1.33	100	4.79	4.62	5.57	0.25	100	14.99	14.44	15.90	0.35	100	15.30	0.04	230.85
	Oct	1.82	0.83	4.81	1.13	50	4.95	4.69	6.18	0.41	50	14.60	14.24	15.07	0.18	50	49.76	0.05	732.78
16	Dec-Jan ¹																		
	Mar											1.49	1.34	1.65	0.09	50	42.39	0.47	252.32
	Apr	0.84	0.59	1.46	0.24	26						2.09	2.01	2.18	0.04	26	0.62	0.08	2.37
	May-June ³	11.53	0.58	63.62	17.11	100	6.82 ⁵	6.32 ⁵	8.38 ⁵	0.68 ⁵	50	8.38	1.91	16.09	6.18	100	4.12 ⁶	0.03 ⁶	97.77 ⁶
	Jul	4.85	0.63	48.24	10.27	50	6.19	5.64	9.44	0.99	50	14.66	14.15	18.67	0.93	50	8.74	0.04	108.70
	Aug	4.07	0.65	21.22	4.18	50	5.79	5.26	9.57	1.00	50	14.24	13.72	18.35	0.96	50	20.61	0.04	442.20
	Sep	1.95	0.87	7.49	1.65	50	4.93	4.76	6.44	0.34	50	14.80	14.19	17.27	0.80	50	8.58	0.03	137.33
	Oct	1.86	0.59	4.91	1.25	50	4.94	4.73	6.07	0.34	50	14.81	14.26	16.71	0.65	50	35.79	0.05	572.29
20	Dec-Jan ¹																		
	Mar ⁴																		
	Apr	18.02	0.71	70.61	25.73	49						2.13	1.92	2.63	0.19	49	4.49	0.02	106.67
	May-June ³	6.64	0.61	73.67	14.60	100	6.75 ⁵	4.97 ⁵	10.73 ⁵	1.91 ⁵	50 ⁵	9.35	2.07	23.07	6.71	100	1.75 ⁶	0.03 ⁶	47.52 ⁶
	Jul	1.02	0.44	6.70	1.37	50	6.57	5.85	10.04	0.98	50	108.75	46.00	246.34	32.97	50	1.47	0.03	70.35
	Aug	1.14	0.43	9.05	1.81	50	6.39	5.92	9.47	0.79	50	72.80	28.32	122.88	27.58	50	22.69	0.03	581.70
	Sep	1.34	0.43	8.27	2.06	50	5.51	5.38	7.37	0.33	50	60.34	23.00	93.07	9.42	50	0.12	0.03	4.05
	Oct	1.35	0.37	6.73	1.84	50	5.19	5.02	6.59	0.28	50	17.68	16.51	27.84	2.13	50	6.43	0.05	164.64

¹No mid-winter cruise occurred in 2009 because no vessel/operator was available.

²No March data from Station 01 because CTD internal memory was inadvertently exceeded.

³To avoid conflicting with the June 1–July 15 closure of upper Muir Inlet to motorized access, the “June” sampling date for Stations 01, 04, 13, 16, and 20 actually occurred on May 31; hence, data from the May and June cruises are averaged together for those stations.

⁴Indicates the station was inaccessible due to the presence of pan ice. Note the absence of a dissolved oxygen sensor until June.

⁵Indicates DO values are from the June cruise only.

⁶Indicates PAR values are from the May cruise only.

⁷PAR sensor disqualified for June.

Table 2a shows that in the upper 50 m of the seven core stations in 2009, mean water temperatures increased from ~3.5–4.0°C in March to ~7.5°C at Stations 01, 04, 13, and 16 in late summer (August–September). At the remaining stations (07, 12, and 20), temperatures did not reach their maxima (~6.7 to ~7.3°C) until October. Temperatures generally increased with distance from the heads of the inlets, toward the mouth of the bay. Salinity generally peaked in spring to early summer (April–June) throughout Glacier Bay, with a somewhat later peak occurring in mid-summer (July) near the mouth of the bay (Station 01). Minimum mean salinities (averaged over the upper 50 m) ranged from 29.24–30.23 PSU; maxima ranged from 30.55–31.79 PSU. As with temperature, salinity generally increased with distance from the heads of the inlets, toward the mouth of the bay. Density (*sigma-t*) decreased throughout the year at all stations until at least October, reflecting the impact of warming (by incoming solar radiation) and freshening (by snowmelt and precipitation) that occurs between spring and fall. Minimum mean densities ranged from 22.92–23.63 kg/m³; maxima ranged from 24.38–25.03 kg/m³. The depth of maximum density gradient is a reasonable proxy for pycnocline depth, where the density changes most rapidly. At most stations in most months this depth was in the upper 11 m. However, in the spring-early summer, for all stations except Stations 12 and 20, depths of maximum gradient occurred at 16–56 m.

Table 2b shows that, in the upper 50 m of the seven core stations in 2009, fluorescence (chlorophyll-*a* concentration, data available starting in April) at most stations peaked in spring or early summer (April–June), but the maximum at Station 04 occurred in August (it is possible that the actual annual peak occurred in March). Peak fluorescence mean values ranged from 8.40–18.02 mg/m³ and were variable along the length-of-bay transect. Dissolved oxygen concentrations (available starting in June) were highest in June and declined thereafter. At Stations 01, 04, 13, and 16 the minima were reached in September (subsequently increasing in October); minimum values at the other stations occurred in October. Dissolved oxygen minimum mean values ranged from 4.36–5.19 ml/L; maxima ranged from 6.20–7.05 ml/L. Values were variable along the length-of-bay transect. Turbidity increased at least until mid-summer (usually July, thence decreasing) at all stations, but at Stations 01, 04, and 16 it increased steadily from March to October. Maximum mean values ranged from 14.81–117.98 NTU; the highest turbidity means were for Stations 12 and 20 (stations close to glacial melt discharge). As might be expected, PAR values through the upper 50 m were highly variable across months and within and among stations, with minimum values approaching 0 µE/cm²*sec, and maxima approaching 900 µE/cm²*sec. Note that PAR values are sensitive to boat shadows, sky cloudiness, and sun elevation, along with water column effects. The only readily evident pattern was that with but a single exception Stations 12 and 20 consistently exhibited the lowest means among all stations for a given month, consistent with the high turbidity values observed at these stations.

Table 3a. 2009 oceanographic data summary of measured parameters (temperature, salinity, density, and fluorescence) at core stations, averaged across a 10-m vertical depth band centered on a representative “bottom water” depth for each station. “Min” and “max” refer to minimum and maximum data values, respectively; “SD” = standard deviation; n = sample size.

Station	Month	Depth (m)	Temperature (°C)					Salinity (PSU)					Density (kg/m ³)					Fluorescence (mg/m ³)				
			Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max	SD	n
01	Dec-Jan ¹	40																				
	Mar ²																					
	Apr		4.00	3.99	4.01	0.01	10	31.55	31.54	31.57	0.01	10	25.04	25.03	25.05	0.01	10	2.96	2.63	3.50	0.26	10
	May-June ³		5.80	5.22	6.38	0.59	20	31.73	31.53	31.96	0.20	20	24.99	24.90	25.10	0.09	20	9.43	2.85	19.43	6.43	20
	Jul		7.11	7.11	7.11	0.00	10	31.89	31.89	31.90	0.00	10	24.96	24.95	24.96	0.00	10	4.13	3.95	4.35	0.14	10
	Aug ⁸																					
	Sep		7.43	7.42	7.43	0.01	10	30.96	30.90	31.09	0.07	10	24.18	24.13	24.29	0.06	10	2.31	2.21	2.49	0.08	10
	Oct		7.25	7.24	7.25	0.00	10	30.30	30.26	30.33	0.02	10	23.68	23.65	23.71	0.02	10	1.82	1.75	1.89	0.06	10
04	Dec-Jan ¹	200																				
	Mar		3.57	3.56	3.59	0.01	10	31.22	31.20	31.25	0.02	10	24.82	24.80	24.84	0.01	10					
	Apr		3.78	3.77	3.80	0.01	10	31.34	31.33	31.35	0.01	10	24.90	24.89	24.90	0.00	10	2.12	1.77	2.57	0.26	10
	May-June ³		4.98	4.45	5.55	0.54	20	31.57	31.51	31.64	0.06	20	24.96	24.94	24.97	0.01	20	1.75	0.84	3.33	0.93	20
	Jul		4.46	4.45	4.47	0.01	10	31.41	31.41	31.41	0.00	10	24.89	24.88	24.89	0.00	10	0.50	0.48	0.51	0.01	10
	Aug		4.69	4.65	4.74	0.03	10	31.36	31.34	31.36	0.01	10	24.82	24.81	24.83	0.01	10	0.43	0.42	0.44	0.01	10
	Sep		5.60	5.52	5.69	0.06	10	31.18	31.17	31.20	0.01	10	24.58	24.56	24.61	0.02	10	0.46	0.45	0.48	0.01	10
	Oct		5.49	5.39	5.55	0.06	10	31.11	31.10	31.14	0.01	10	24.54	24.53	24.57	0.01	10	0.41	0.40	0.43	0.01	10
07	Dec-Jan ¹	200																				
	Mar		3.61	3.61	3.62	0.00	10	31.19	31.19	31.20	0.00	10	24.80	24.79	24.80	0.00	10					
	Apr		3.71	3.71	3.71	0.00	10	31.30	31.30	31.30	0.00	10	24.87	24.87	24.87	0.00	10	0.92	0.91	0.95	0.01	10
	May		4.07	4.05	4.08	0.01	10	31.47	31.46	31.47	0.00	10	24.97	24.97	24.97	0.00	10	0.71	0.67	0.78	0.03	10
	Jun		4.11	4.10	4.11	0.00	10	31.45	31.44	31.45	0.00	10	24.95	24.95	24.95	0.00	10	0.45	0.43	0.49	0.02	10
	Jul		4.18	4.17	4.20	0.01	10	31.36	31.34	31.37	0.01	10	24.87	24.86	24.88	0.01	10	0.41	0.40	0.43	0.01	10
	Aug ⁸																					
	Sep		4.87	4.76	5.04	0.10	10	31.26	31.24	31.28	0.02	10	24.73	24.69	24.75	0.02	10	0.38	0.36	0.39	0.01	10
	Oct		5.15	5.13	5.18	0.02	10	31.08	31.07	31.09	0.01	10	24.55	24.54	24.56	0.01	10	0.35	0.34	0.36	0.01	10
12	Dec-Jan ¹	200																				
	Mar ⁴																					
	Apr ⁴																					
	May		3.85	3.84	3.86	0.01	10	31.40	31.39	31.40	0.00	10	24.94	24.93	24.94	0.00	10	0.76	0.68	0.89	0.06	10
	Jun		3.88	3.88	3.88	0.00	10	31.38	31.38	31.39	0.00	10	24.92	24.92	24.92	0.00	10	0.55	0.51	0.63	0.04	10
	Jul		4.01	4.01	4.02	0.01	10	31.22	31.21	31.23	0.01	10	24.78	24.77	24.78	0.01	10	0.55	0.55	0.56	0.01	10
	Aug		4.59	4.59	4.59	0.00	10	30.86	30.85	30.86	0.00	10	24.43	24.43	24.44	0.00	10	0.57	0.56	0.59	0.01	10
	Sep		4.54	4.53	4.57	0.02	10	31.02	31.00	31.03	0.01	10	24.57	24.55	24.57	0.01	10	0.34	0.32	0.38	0.02	10
	Oct		4.50	4.48	4.52	0.01	10	31.01	31.00	31.02	0.01	10	24.57	24.55	24.58	0.01	10	0.31	0.31	0.32	0.01	10

Table 3a. 2009 oceanographic data summary of measured parameters (temperature, salinity, density, and fluorescence) at core stations, averaged across a 10-m vertical depth band centered on a representative “bottom water” depth for each station. “Min” and “max” refer to minimum and maximum data values, respectively; “SD” = standard deviation; n = sample size.

Station	Month	Depth (m)	Temperature (°C)					Salinity (PSU)					Density (kg/m ³)					Fluorescence (mg/m ³)				
			Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max	SD	n
13	Dec-Jan ¹	100																				
	Mar		3.58	3.58	3.59	0.00	10	31.18	31.17	31.20	0.01	10	24.79	24.78	24.80	0.01	10					
	Apr		3.72	3.72	3.72	0.00	10	31.26	31.26	31.27	0.00	10	24.84	24.84	24.84	0.00	10	1.17	1.08	1.33	0.07	10
	May-June ³		4.43	4.21	4.77	0.23	20	31.43	31.42	31.44	0.01	20	24.90	24.87	24.93	0.02	20	0.98	0.60	1.66	0.37	20
	Jul		5.28	5.17	5.36	0.05	10	31.32	31.30	31.33	0.01	10	24.73	24.70	24.74	0.01	10	0.78	0.75	0.83	0.03	10
	Aug		6.07	5.95	6.15	0.08	10	31.25	31.24	31.27	0.01	10	24.58	24.56	24.61	0.02	10	0.63	0.60	0.65	0.02	10
	Sep		6.34	6.24	6.49	0.06	20	30.96	30.91	30.99	0.02	20	24.32	24.26	24.36	0.03	20	0.60	0.56	0.70	0.04	20
	Oct		6.68	6.61	6.74	0.05	10	30.70	30.67	30.74	0.02	10	24.07	24.04	24.11	0.02	10	0.55	0.53	0.56	0.01	10
16	Dec-Jan ¹	200																				
	Mar		3.68	3.67	3.68	0.00	10	31.04	31.04	31.04	0.00	10	24.67	24.67	24.67	0.00	10					
	Apr		3.67	3.67	3.67	0.00	10	31.12	31.11	31.12	0.00	10	24.73	24.73	24.73	0.00	10	0.92	0.86	0.97	0.03	10
	May-June ³		3.95	3.92	4.00	0.03	20	31.31	31.30	31.32	0.01	20	24.86	24.85	24.86	0.00	20	0.84	0.43	1.40	0.40	20
	Jul		3.99	3.98	3.99	0.00	10	31.29	31.29	31.29	0.00	10	24.84	24.84	24.84	0.00	10	0.35	0.33	0.36	0.01	10
	Aug		4.06	4.05	4.06	0.00	10	31.28	31.28	31.28	0.00	10	24.82	24.82	24.83	0.00	10	0.35	0.34	0.36	0.01	10
	Sep		4.30	4.29	4.31	0.01	10	31.23	31.23	31.24	0.00	10	24.76	24.76	24.76	0.00	10	0.42	0.41	0.43	0.01	10
	Oct		4.62	4.61	4.65	0.01	10	31.13	31.13	31.14	0.01	10	24.65	24.64	24.66	0.01	10	0.37	0.36	0.38	0.01	10
20	Dec-Jan ¹	125																				
	Mar ⁴																					
	Apr		3.67	3.67	3.67	0.00	10	31.06	31.05	31.06	0.00	10	24.68	24.68	24.68	0.00	10	0.64	0.62	0.68	0.02	10
	May-June ³		3.81	3.73	3.89	0.08	20	31.25	31.20	31.28	0.03	20	24.82	24.79	24.84	0.02	20	0.61	0.54	0.68	0.04	20
	Jul		4.02	4.02	4.02	0.00	10	31.10	31.10	31.10	0.00	10	24.68	24.68	24.69	0.00	10	0.39	0.38	0.39	0.00	10
	Aug		4.31	4.28	4.34	0.02	10	31.02	31.01	31.03	0.01	10	24.59	24.58	24.60	0.01	10	0.38	0.36	0.38	0.01	10
	Sep		4.76	4.66	4.84	0.07	10	30.93	30.90	30.97	0.02	10	24.47	24.45	24.51	0.03	10	0.43	0.42	0.45	0.01	10
	Oct		4.77	4.71	4.84	0.04	10	30.96	30.94	30.99	0.02	10	24.50	24.48	24.52	0.02	10	0.36	0.35	0.37	0.01	10

¹No mid-winter cruise occurred in 2009 because no vessel/operator was available.

²No March data from Station 01 because CTD internal memory was inadvertently exceeded.

³To avoid conflicting with the June 1 – July 15 closure of upper Muir Inlet to motorized access, the “June” sampling date for Stations 01, 04, 13, 16, and 20 actually occurred on May 31; hence, data from the May and June cruises are averaged together for those stations.

⁴Indicates the station was inaccessible due to the presence of pan ice.

⁸CTD failed to reach target depth.

Table 3b. 2009 oceanographic data summary of measured parameters (dissolved oxygen, OBS, and PAR) at core stations, averaged across a 10-m vertical depth band centered on a representative “bottom water” depth for each station. “Min” and “max” refer to minimum and maximum data values, respectively; “SD” = standard deviation; n = sample size. Note the absence of the SD statistic for PAR (decreases exponentially from the surface, so SD has little meaning).

Station	Month	Depth (m)	Dissolved Oxygen (mg/L)					OBS (NTU)					PAR ($\mu\text{E}/\text{cm}^2 \cdot \text{s}$)		
			Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max
01	Dec-Jan ¹	40													
	Mar ²														
	Apr							3.10	3.02	3.23	0.05	10	0.05	0.04	0.08
	May-June ³		5.97 ⁵	5.93 ⁵	6.06 ⁵	0.04 ⁵	10 ⁵	10.24	3.20	17.24	7.11	20	0.04 ⁶	0.04 ⁶	0.04 ⁶
	Jul		4.71	4.70	4.71	0.00	10	15.31	15.23	15.37	0.05	10	0.07	0.05	0.09
	Aug ⁸														
	Sep		4.19	4.11	4.24	0.05	10	17.47	17.13	17.88	0.19	10	0.03	0.03	0.04
	Oct		4.77	4.77	4.78	0.01	9	18.48	18.13	18.81	0.24	10	0.04	0.04	0.04
04	Dec-Jan ¹	200													
	Mar							1.86	1.77	1.98	0.07	10	0.02	0.02	0.02
	Apr							3.39	3.27	3.67	0.14	10	0.03	0.03	0.03
	May-June ³		6.40 ⁵	6.38 ⁵	6.43 ⁵	0.02 ⁵	10 ⁵	10.37	3.74	16.69	6.41	20	0.03 ⁶	0.03 ⁶	0.03 ⁶
	Jul		5.86	5.86	5.86	0.00	10	15.46	15.38	15.53	0.04	10	0.05	0.05	0.05
	Aug		5.63	5.62	5.64	0.01	10	14.19	14.07	14.26	0.05	10	0.05	0.05	0.05
	Sep		5.19	5.17	5.21	0.01	10	14.67	14.47	14.99	0.16	10	0.04	0.04	0.04
	Oct		5.08	5.06	5.11	0.02	10	15.60	15.54	15.65	0.03	10	0.04	0.04	0.04
07	Dec-Jan ¹	200													
	Mar							1.43	1.36	1.48	0.04	10	0.03	0.03	0.03
	Apr							2.60	2.50	2.69	0.06	10	0.03	0.03	0.03
	May							2.23	2.15	2.33	0.06	10	0.04	0.04	0.04
	Jun ⁷		6.41	6.40	6.41	0.00	10	12.99	12.96	13.02	0.02	10			
	Jul		5.92	5.91	5.93	0.00	10	15.02	14.95	15.05	0.03	10	0.04	0.04	0.04
	Aug ⁸														
	Sep		5.49	5.45	5.52	0.02	10	14.86	14.78	14.93	0.05	10	0.04	0.04	0.04
	Oct		5.37	5.37	5.38	0.00	10	15.26	15.20	15.33	0.04	10	0.04	0.04	0.04
12	Dec-Jan ¹	200													
	Mar ³														
	Apr ³														
	May							3.47	3.24	3.61	0.13	10	0.03	0.03	0.03
	Jun ⁷		6.22	6.22	6.23	0.00	10	16.80	16.32	17.22	0.36	10			
	Jul		6.00	5.99	6.00	0.00	10	67.09	64.22	70.32	2.41	10	0.03	0.03	0.03
	Aug		5.99	5.98	5.99	0.00	10	221.52	220.89	222.13	0.43	10	0.05	0.05	0.05
	Sep		5.70	5.70	5.71	0.00	10	106.18	95.69	112.88	7.28	10	0.03	0.03	0.03
	Oct		5.59	5.59	5.59	0.00	10	16.50	15.99	17.05	0.37	10	0.03	0.03	0.03

Table 3b. 2009 oceanographic data summary of measured parameters (dissolved oxygen, OBS, and PAR) at core stations, averaged across a 10-m vertical depth band centered on a representative “bottom water” depth for each station. “Min” and “max” refer to minimum and maximum data values, respectively; “SD” = standard deviation; n = sample size. Note the absence of the SD statistic for PAR (decreases exponentially from the surface, so SD has little meaning) (continued).

Station	Month	Depth (m)	Dissolved Oxygen (mg/L)					OBS (NTU)					PAR ($\mu\text{E}/\text{cm}^2 \cdot \text{s}$)		
			Mean	Min	Max	SD	n	Mean	Min	Max	SD	n	Mean	Min	Max
13	Dec-Jan ¹	100													
	Mar							1.49	1.38	1.62	0.08	10	0.02	0.02	0.02
	Apr							2.04	1.97	2.13	0.04	10	0.02	0.02	0.02
	May-June ³		6.53 ⁵	6.53 ⁵	6.54 ⁵	0.00 ⁵	10 ⁵	8.47	2.01	14.99	6.57	20	0.03 ⁶	0.03 ⁶	0.03 ⁶
	Jul		5.79	5.78	5.79	0.00	10	14.97	14.89	15.03	0.04	10	0.05	0.05	0.05
	Aug ⁸		5.20	5.19	5.22	0.01	10	13.75	13.67	13.78	0.04	10	0.04	0.04	0.04
	Sep		4.90	4.86	4.93	0.02	20	14.53	14.41	14.76	0.10	20	0.04	0.04	0.04
	Oct		4.71	4.69	4.72	0.01	10	15.00	14.96	15.05	0.03	10	0.03	0.03	0.03
16	Dec-Jan ¹	200													
	Mar							1.62	1.58	1.71	0.04	10	0.03	0.03	0.03
	Apr							2.63	2.54	2.75	0.06	10	0.02	0.02	0.02
	May-June ³		6.39 ⁵	6.39 ⁵	6.40 ⁵	0.00 ⁵	10 ⁵	8.37	2.35	14.38	6.05	20	0.03 ⁶	0.03 ⁶	0.03 ⁶
	Jul		6.01	6.01	6.02	0.00	10	14.77	14.60	14.96	0.11	10	0.04	0.04	0.04
	Aug		5.89	5.88	5.89	0.00	10	13.95	13.89	14.07	0.05	10	0.04	0.04	0.04
	Sep		5.64	5.63	5.64	0.00	10	14.40	14.35	14.47	0.04	10	0.03	0.03	0.03
	Oct		5.47	5.46	5.47	0.00	10	14.94	14.83	15.08	0.08	10	0.04	0.04	0.04
20	Dec-Jan ¹	125													
	Mar ⁴							2.32	2.12	2.56	0.16	10	0.02	0.02	0.02
	Apr							9.30	2.60	16.03	6.75	20	0.03 ⁶	0.03 ⁶	0.03 ⁶
	May-June ³		6.29 ⁵	6.28 ⁵	6.29 ⁵	0.00 ⁵	10 ⁵	79.75	78.19	81.93	1.31	10	0.04	0.04	0.04
	Jul		5.82	5.81	5.82	0.00	10	107.57	103.56	112.06	2.76	10	0.03	0.03	0.03
	Aug		5.77	5.76	5.77	0.00	10	95.34	92.59	98.07	2.00	10	0.03	0.03	0.03
	Sep		5.53	5.52	5.54	0.01	10	17.82	17.60	18.00	0.13	10	0.05	0.05	0.05
	Oct		5.43	5.42	5.43	0.00	10								

¹No mid-winter cruise occurred in 2009 because no vessel/operator was available.

²No March data from Station 01 because CTD internal memory was inadvertently exceeded.

³To avoid conflicting with the June 1 – July 15 closure of upper Muir Inlet to motorized access, the “June” sampling date for Stations 01, 04, 13, 16, and 20 actually occurred on May 31; hence, data from the May and June cruises are averaged together for those stations.

⁴Indicates the station was inaccessible due to the presence of pan ice. Note the absence of a dissolved oxygen sensor until June.

⁵Indicates DO values are from the June cruise only.

⁶Indicates PAR values are from the May cruise only.

⁷PAR sensor disqualified for June.

⁸CTD failed to reach target depth.

Table 3a shows that, for the bottom water at the seven core stations in 2009, mean water temperatures increased throughout the year to late summer/early fall maxima at the head of the West Arm (Station 12, August) and in lower Glacier Bay (Stations 01 and 04, September); temperatures increased until at least October at the remaining stations. For all stations, temperatures increased across the season by $\sim 0.7\text{--}3.4^{\circ}\text{C}$. Annual minima ranged from $\sim 3.6\text{--}4.0^{\circ}\text{C}$; maxima ranged from $\sim 4.6\text{--}7.4^{\circ}\text{C}$. Relative temperatures generally increased with distance from the heads of the inlets, toward the mouth of the bay. Salinity generally peaked in late spring to early summer (May–June) throughout Glacier Bay, with the peak occurring in mid-summer (July) near the mouth of the bay (Station 01). Minimum mean salinities ranged from 30.3–31.11 PSU; maxima ranged from 31.25–31.89 PSU. As with temperature, salinity generally increased with distance from the heads of the inlets, toward the mouth of the bay. Unlike in the near-surface (upper 50 m) waters, minimum mean density (*sigma-t*) did not always occur at the end of the year; instead, minima at Stations 12 and 20 occurred in August and September, respectively. Minimum mean densities ranged from 23.68–24.65 kg/m^3 ; maxima ranged from 24.82–25.04 kg/m^3 . As was observed in the near-surface waters, fluorescence (chlorophyll-*a* concentration, data available starting in April) at depth peaked in spring to early summer (April–June) across stations. Peak fluorescence mean values ranged from 0.64–9.43 mg/m^3 , generally decreased throughout the year, and were lowest at the heads of the inlets and highest in the lower bay where the entire water column can be homogenized by strong tidal stirring.

Table 3b shows that, for the bottom water at the seven core stations in 2009, dissolved oxygen concentrations (available starting in June) were highest in June and declined thereafter throughout the year (except the minimum mean value at Station 01 occurred in September rather than October). Dissolved oxygen minimum mean values ranged from 4.19–5.59 ml/L ; maxima ranged from 5.97–6.53 ml/L . Values were variable along the length-of-bay transect, but Station 01 showed both the lowest minima and maxima throughout the year, and Station 13 showed the second lowest minimum and highest maximum. Turbidity increased from March until October, except at Stations 12 and 20 where it peaked in late-summer (August) and then decreased. Maximum mean values ranged from 14.94–221.52 NTU; the highest turbidity means were for Stations 12 and 20. As might be expected, PAR values at depth were quite low (approaching 0 $\mu\text{E/cm}^2\cdot\text{sec}$) at all stations in all months.

Figure 3 provides example vertical profiles of temperature, salinity, and density from a single mid-bay station (Station 04; see Figure 2) during the month of July, plotted alongside the historical mean values for the same parameters from this station in July for the period of 1993 through 2008. This station and month were identified in the oceanographic monitoring protocol for greater in-depth analysis on a yearly basis.

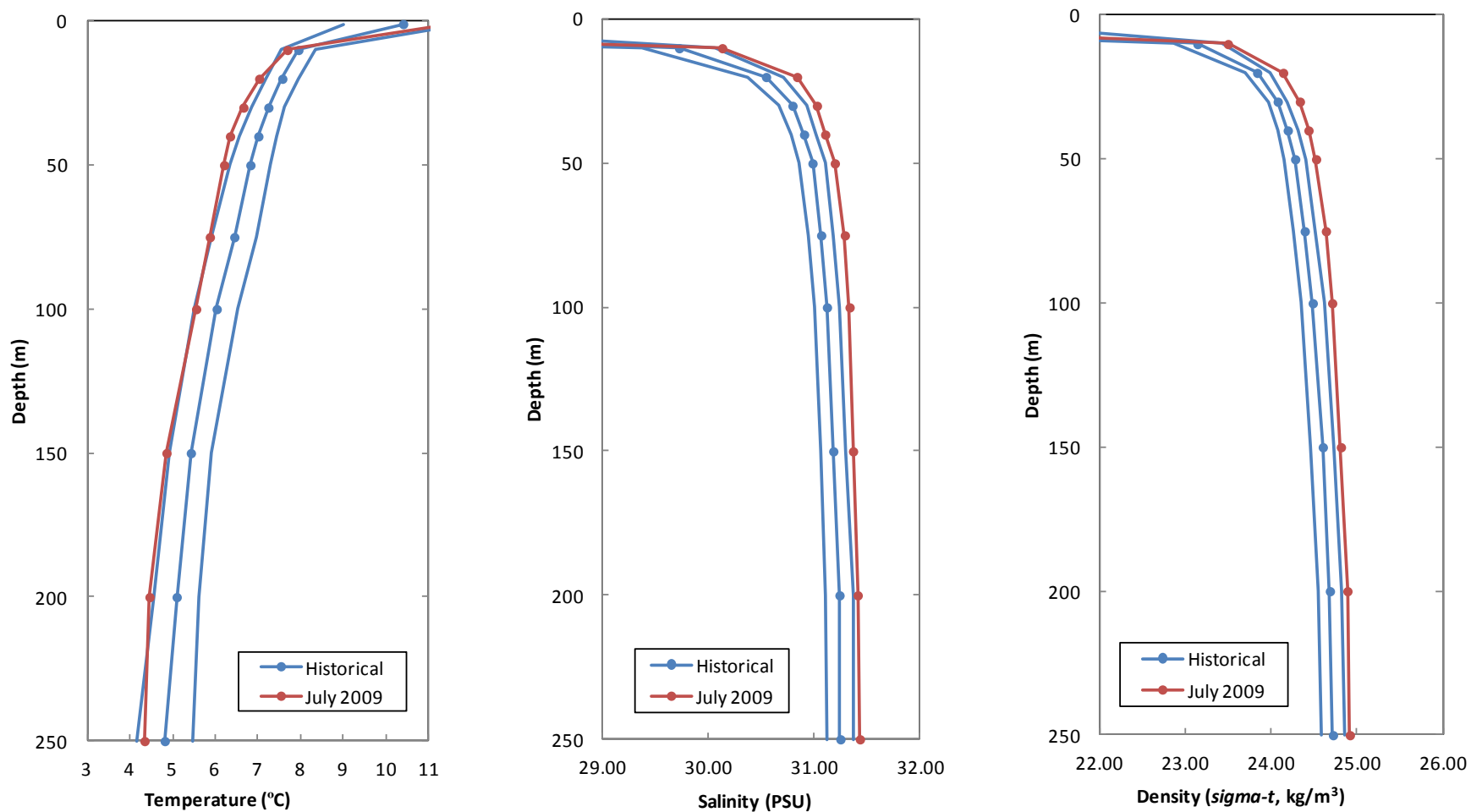


Figure 3. Vertical profiles of temperature (left), salinity (center), and density ($\sigma\text{-}t$, right) shown along with historical data (means for July 1993–2008, Station 04). 2009 data are shown in red with dots; historical means are blue with dots along with +/- bounds of one standard deviation to either side (blue, without dots). Only a subset of the full vertical profile is shown here, using standard depths of 0, 10, 20, 30, 50, 75, 100, 150, 200, and 250 m.

We describe current-year data as “normal” when the data values fall within one standard deviation of the historical mean (1993–2008) and anomalous otherwise. Figure 3 clearly shows that waters at this station in July of 2009 were anomalously cold, saline, and dense below the upper 10 m.

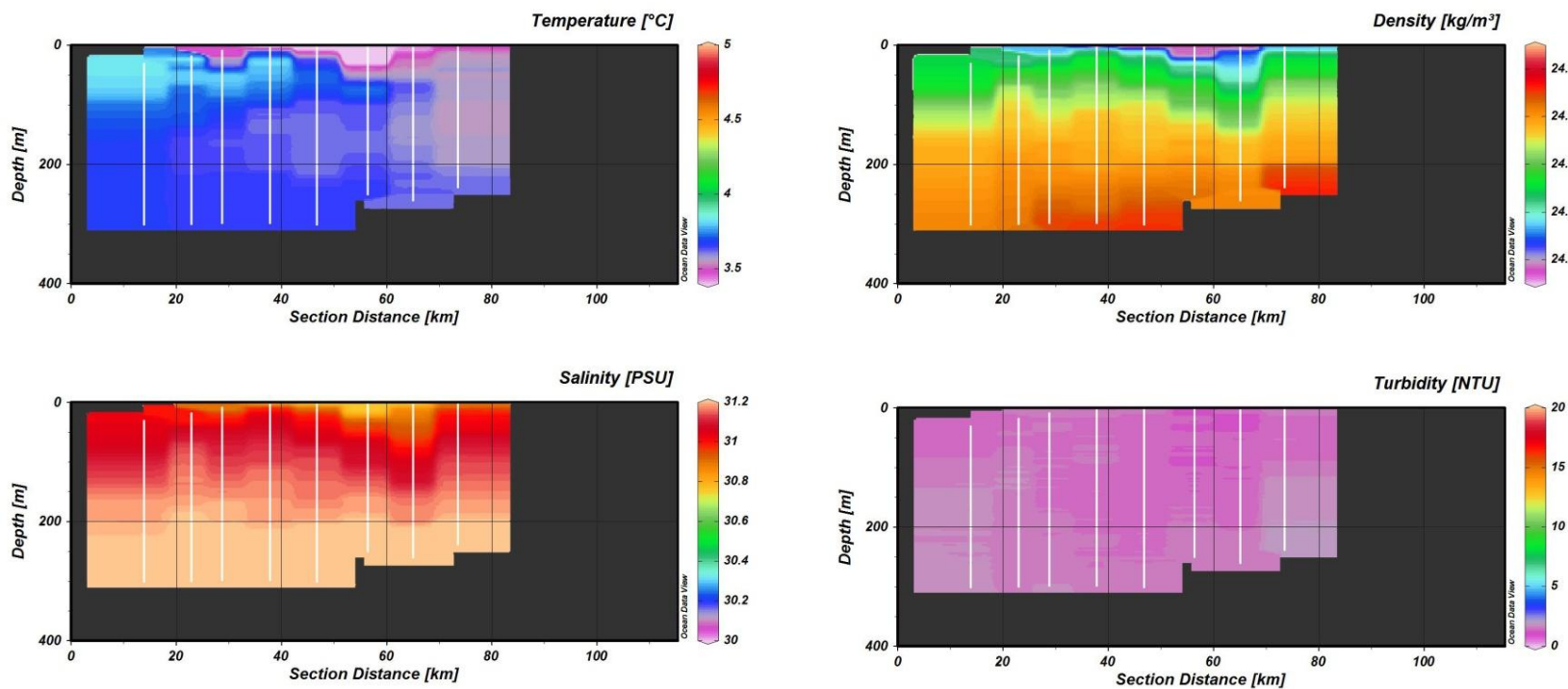
Table 4 displays the numerical values plotted in Figure 3.

Table 4. Temperature, salinity, and density measurements from standard depths at Station 04 in July 2009, compared to historical measurements from that station in July, 1993–2008. To help draw attention to anomalous measurements, July 2009 observations lying outside one standard deviation (SD) of the long-term mean are emphasized in ***bold, italic type***. n = sample size.

Depth (m)	Station 04 Temperature (°C)					Station 04 Salinity (PSU)					Station 04 Density (kg/m ³)				
	July 2009	Historic July mean	Historic mean -1 SD	Historic mean +1 SD	n	July 2009	Historic July mean	Historic mean -1 SD	Historic mean +1 SD	n	July 2009	Historic July mean	Historic mean -1 SD	Historic mean +1 SD	n
1 ¹	11.44	10.40	9.01	11.79	13	21.61	22.46	19.01	25.91	13	16.30	17.12	14.34	19.90	13
10	7.68	7.94	7.55	8.33	13	<i>30.13</i>	29.72	29.37	30.07	13	<i>23.49</i>	23.14	22.86	23.42	13
20	<i>7.03</i>	7.57	7.18	7.95	13	<i>30.84</i>	30.54	30.37	30.72	13	<i>24.14</i>	23.83	23.69	23.98	13
30	<i>6.65</i>	7.24	6.85	7.63	13	<i>31.02</i>	30.79	30.66	30.93	13	<i>24.33</i>	24.07	23.96	24.19	13
40	<i>6.34</i>	7.01	6.58	7.43	13	<i>31.10</i>	30.90	30.79	31.02	13	<i>24.43</i>	24.19	24.08	24.31	13
50	<i>6.20</i>	6.82	6.34	7.30	13	<i>31.19</i>	30.98	30.86	31.11	13	<i>24.52</i>	24.28	24.15	24.41	13
75	<i>5.87</i>	6.44	5.92	6.96	13	<i>31.29</i>	31.06	30.95	31.18	13	<i>24.64</i>	24.39	24.26	24.52	13
100	5.55	6.03	5.52	6.54	12	<i>31.33</i>	31.12	31.00	31.24	12	<i>24.71</i>	24.48	24.35	24.61	12
150	<i>4.85</i>	5.42	4.93	5.91	12	<i>31.36</i>	31.18	31.06	31.30	12	<i>24.81</i>	24.60	24.46	24.73	12
200	<i>4.46</i>	5.09	4.56	5.62	11	<i>31.41</i>	31.24	31.11	31.36	11	<i>24.89</i>	24.68	24.55	24.82	11
250	4.34	4.81	4.15	5.47	5	<i>31.43</i>	31.25	31.12	31.37	5	<i>24.91</i>	24.72	24.58	24.85	5

¹The standard depth of 0 m has been replaced by 1 m to provide complete and consistent data for analysis. Given the objective of characterizing the surface water, 1 m is a reasonable proxy for 0 m.

Horizontal cross-sections provide effective at-a-glance visual depictions of water column parameters as a function of depth and distance along the transect. Figure 4 shows colored contour plots of two length-of-bay transects at two different times of year. These plots incorporate data from all stations along their respective transects; all 22 oceanographic stations are occupied during mid-winter and mid-summer cruises.



(a) March 2009 East Arm

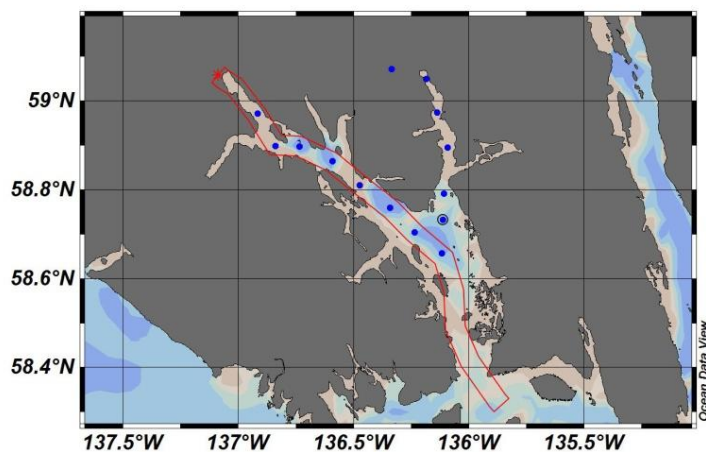
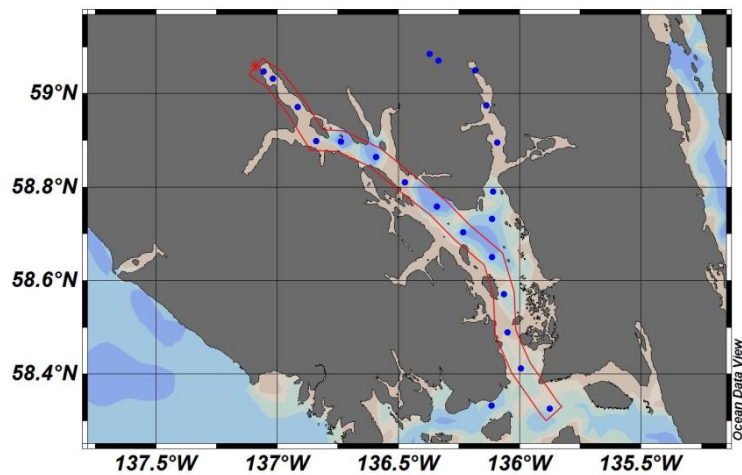
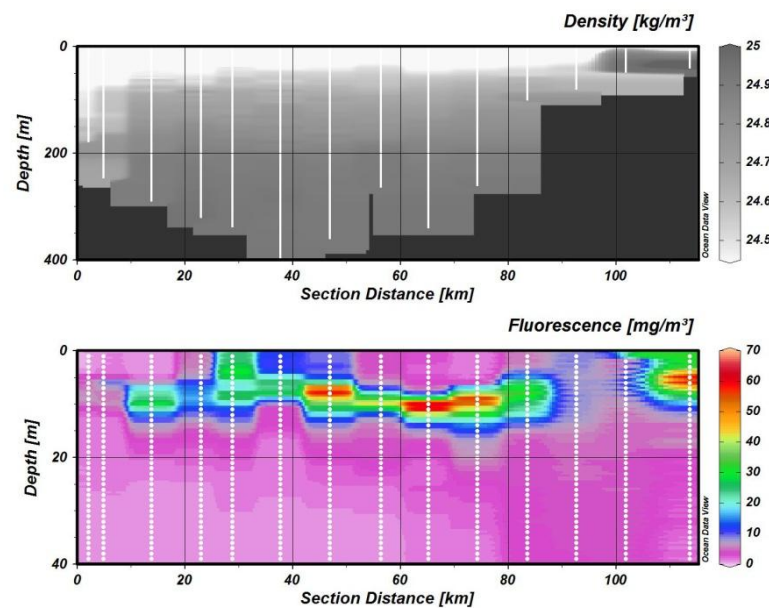
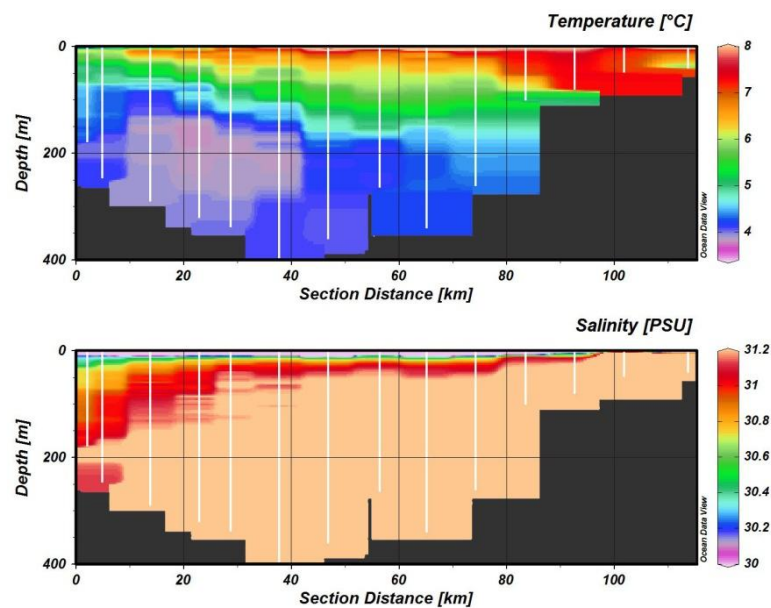
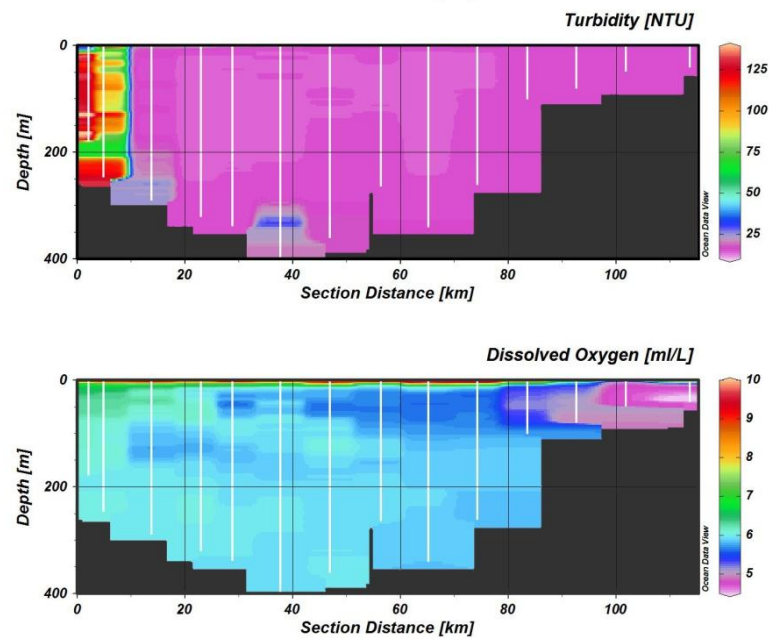
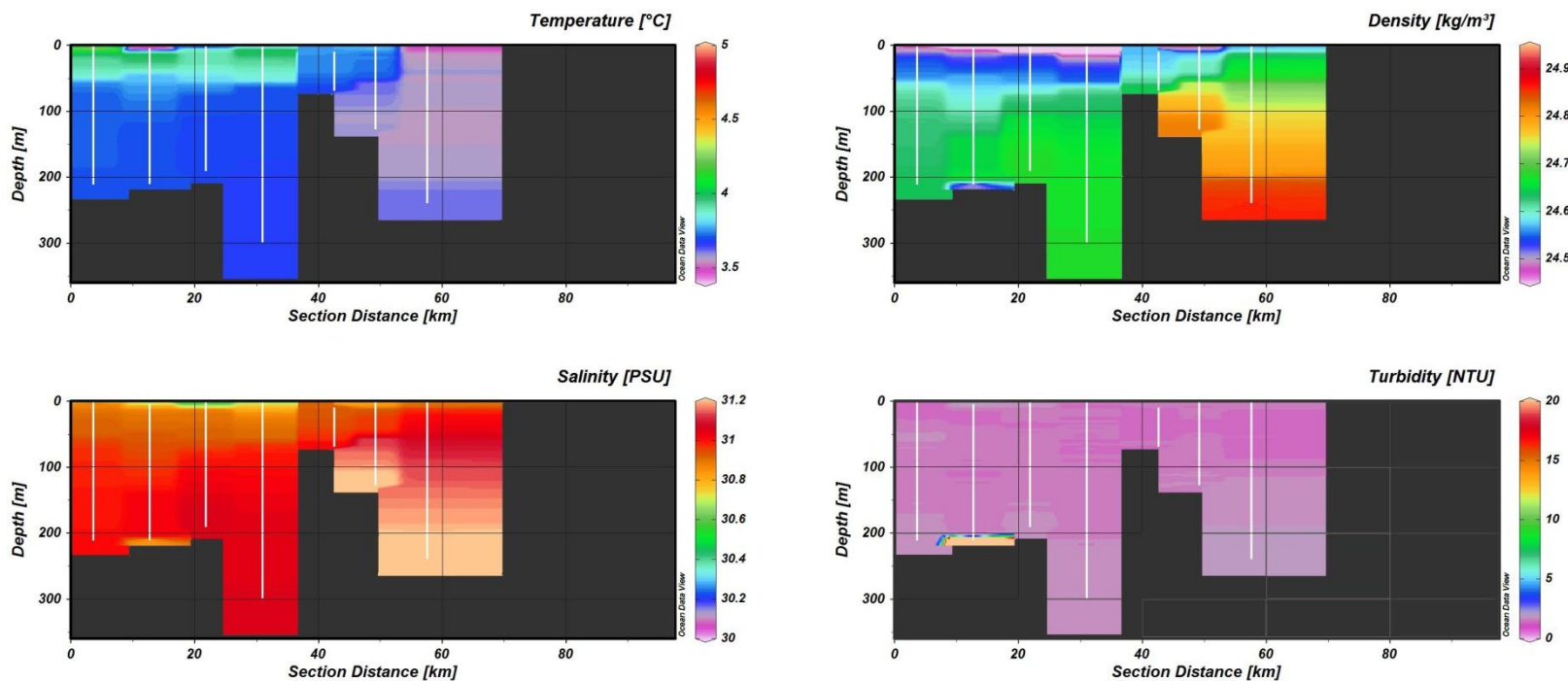


Figure 4. Length-of-transect cross-sectional contour plots of principal oceanographic parameters for the West Arm transect for (a) March 2009, and (b) July 2009. Station locations are plotted with blue dots on the map at bottom-left for each set, and the transect is outlined in red. On the contour plots, the mouth of Glacier Bay (Station 00) is located at 0 km on the horizontal axis. Gray/black, squared-off areas of the plots indicate the bottom or an absence of data (e.g., missed stations, shallow casts, disqualified sensors). White vertical lines indicate station locations. Special note regarding the transect maps: Figure 4a does not show all station locations due to a software limitation.



(b) July 2009 West Arm





(a) March 2009 East Arm

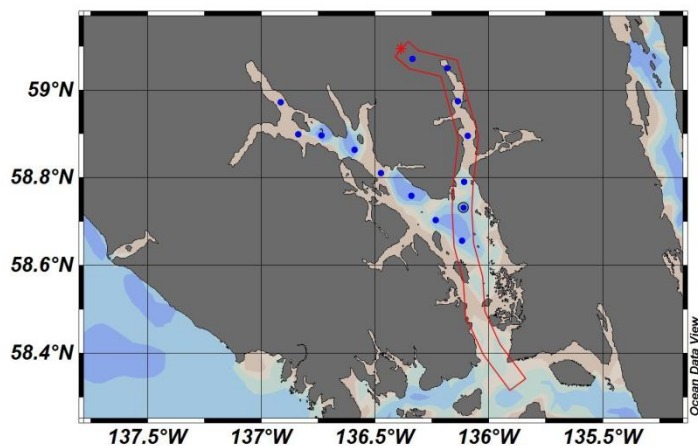
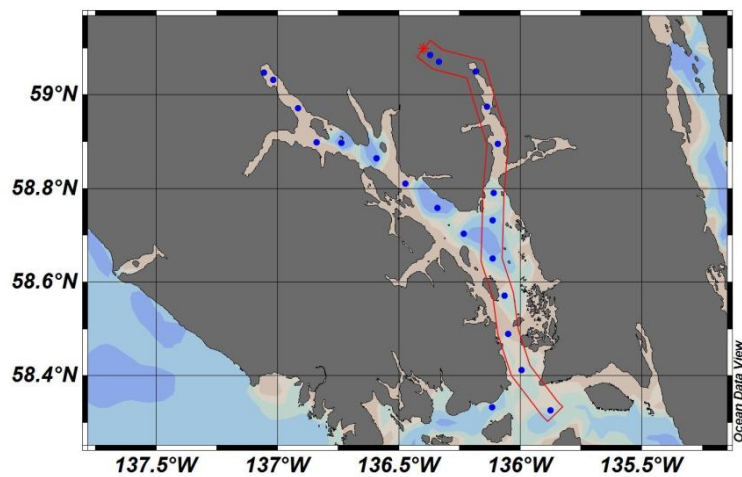
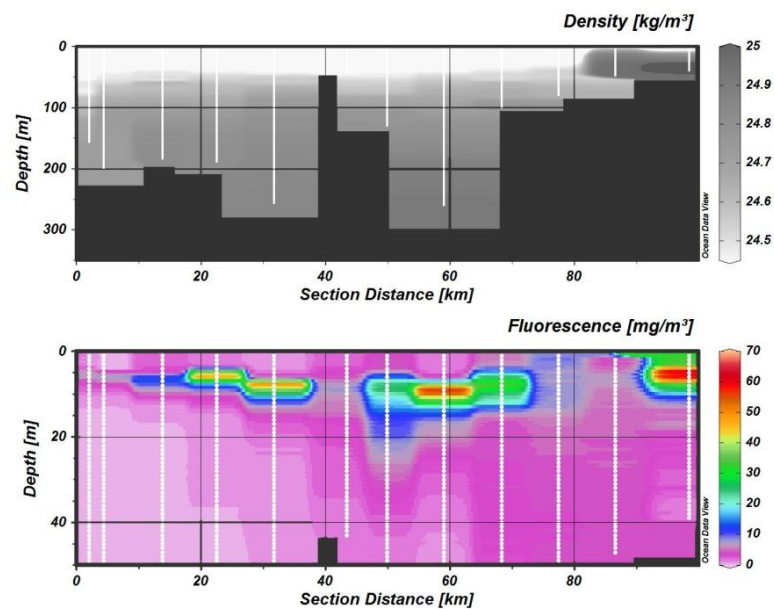
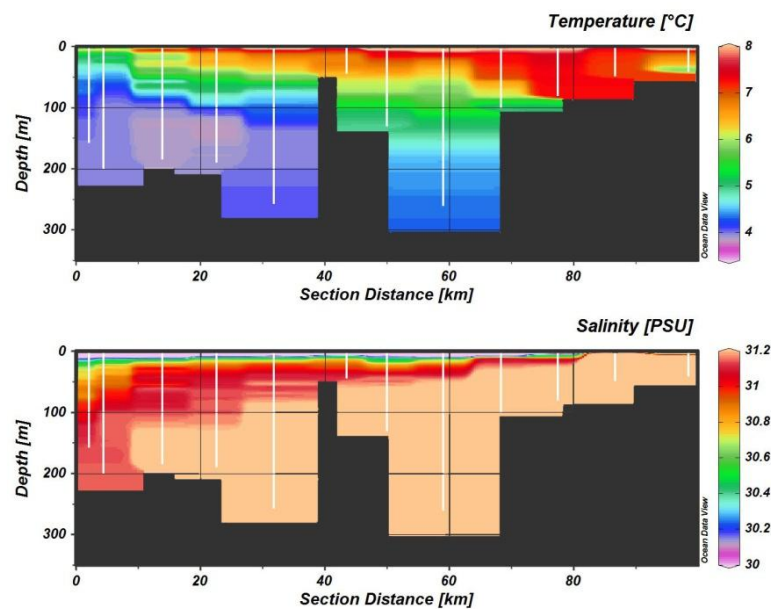


Figure 5. Length-of-transect cross-sectional contour plots of principal oceanographic parameters across the East Arm transect for (a) March 2009, and (b) July 2009. Station locations are plotted with blue dots on the map at bottom-left for each set, and the transect is outlined in red. On the contour plots, the mouth of Glacier Bay (Station 00) is located at 0 km on the horizontal axis. Gray/black, squared-off areas of the plots indicate the bottom or an absence of data (e.g., missed stations, shallow casts, disqualified sensors). White vertical lines indicate station locations. Special notes regarding the transect maps: the dated base map fails to reflect the present-day extent of upper Muir Inlet exposed by tidewater glacial recession, but it is coarsely indicated in red (see also Figure 2); Figure 5a does not show all station locations due to a software limitation.



(b) July 2009 East Arm

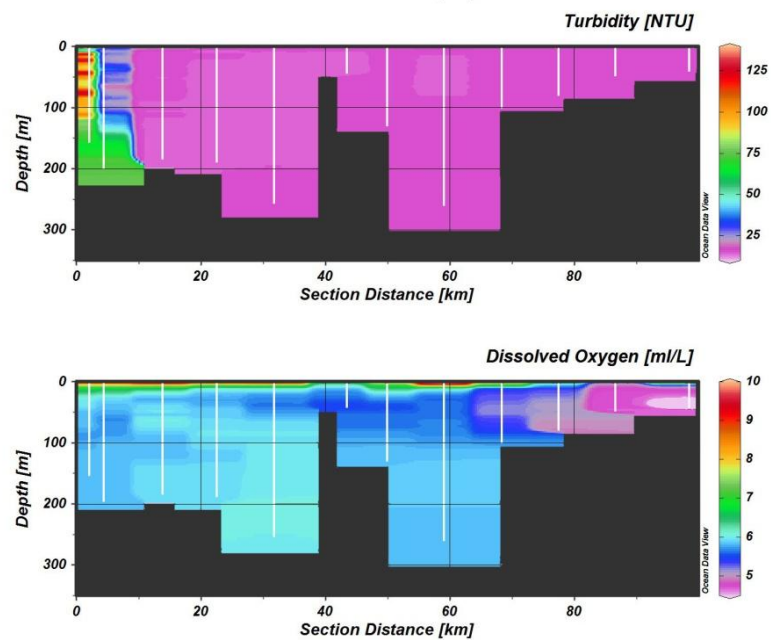


Figure 4a (West Arm transect in March) clearly shows relatively cold temperatures throughout the water column at all stations, and a trend of decreasing temperatures with proximity to the head of the West Arm. Salinity and density were relatively high across all depths at all stations, with a tendency toward increasing salinity/density with depth; however, no strong pycnocline was evident. In general, the water column was relatively well-mixed. There were no strong along-transect trends except in terms of a general cooling with proximity to the upper inlet. Turbidity was very low at all depths and across all stations in March. Fluorescence and dissolved oxygen data were unavailable for this month.

In mid-summer (July), the West Arm transect looks dramatically different (Figure 4b). Waters were substantially warmer throughout the water column, and there was considerable vertical structure along the entire transect. Increased temperatures and decreased salinities were most noticeable in the surface waters, and a strong near-surface pycnocline had developed across the entire transect. Apparent bloom conditions were established, with relatively high levels of fluorescence in the near-surface waters (generally the upper 15 m; note the change in the vertical depth axis), especially in the mid-bay and extreme upper inlet. Turbidity also was much higher compared to March, especially near the mouth of the bay and at depth in the lower to central parts of the main trunk of Glacier Bay. Dissolved oxygen was high across the entire transect with no indication of anoxia at depth. Lower concentrations were evident in the near-surface waters, and this region of slightly decreased oxygen shoaled toward the mouth of the bay.

The East Arm transect in March (Figure 5a) looks much like the West Arm for that month (Figure 4a). Note that although surface waters were somewhat cooler and less saline, these properties tended to compensate for one another in terms of their contributions to the density structure, and there was no strong pycnocline. The water column was generally well-mixed. There was a general trend of cooling with distance from the mouth of the bay. As with the West Arm transect in March, turbidity levels were generally low at all depths and across all stations, and fluorescence and dissolved data were absent.

Figure 5b shows conditions along the East Arm transect in mid-summer (July). As with the mid-summer West Arm transect, compared to March conditions the water temperatures had warmed considerably, surface salinities had declined, and vertical structure was well-developed. Relatively high fluorescence levels occurred near the surface, especially mid-bay and in the upper inlet. Turbidity levels were substantially higher than in March, especially near the mouth of the bay. Dissolved oxygen was high across the entire transect with no indication of anoxia at depth. Lower concentrations were evident in the near-surface waters, and this region of slightly decreased oxygen was increasingly shallow with distance from the mouth of the bay and toward the head of the inlet.

Discussion

Oceanographic parameters are measured by sensors that are very precise and have very high calibrated accuracy. In cases where sensors do not directly measure parameters of interest (e.g., suspended particulate concentration), they have been shown to measure a closely correlated proxy (e.g., optical backscatterance, or turbidity). However, it is important to understand that because water column samples of phytoplankton, suspended sediment, and dissolved oxygen are not collected and analyzed, data from these ancillary sensors cannot be quantitatively compared with high rigor on an inter-cruise or inter-annual basis, nor even at times within the same cruise/survey because many factors, including differing phytoplankton species assemblages and the state of health of the cells also impact the fluorescence response. The cycles of phytoplankton bloom and decline are unavoidably aliased with this (monthly) monitoring program. In addition, the phytoplankton assemblage being measured at any given place and time is ephemeral; the same measurement taken a day, a week, or two weeks earlier or later could bear little or no resemblance to the measurements taken on the date of the cruise. Nevertheless, with these caveats in mind, we can still recognize coarse patterns and gross trends because 1) high-latitude glacial fjords typically exhibit relatively strong seasonal and inter-annual signals, and 2) expected parameter trends along the length-of-fjord transect are generally well understood (Syvitsky et al. 1987).

In 2009, most measured parameters did not exhibit extreme departures from the range of variation observed in Glacier Bay in previous years (Etherington et al. 2007). An important exception, however, was that waters in the central bay (Station 04) were anomalously cold, saline, and dense below the upper 10 m in mid-summer (Figure 3; Table 4), compared to the 1993–2008 historical mean. Surface and bottom waters of the bay are generally isolated from one another for much of the year due to strong vertical stratification. Waters entering the bay are strongly mixed as they transit Sitakaday Narrows (Figure 1 - vicinity of Station 02, 3.5 km width, 75 m maximum channel depth) on their way to the 300 m+ deep Station 04 basin. Because the cold and salty anomaly is observed across such a wide range of depths, it suggests the influence of external forcing from outside Glacier Bay proper and/or the impact of water column homogenization during the course of the previous winter (University of Alaska-Fairbanks, S. Danielson, pers. comm., 2011). Waters entering the bay are strongly mixed as they transit Sitakaday Narrows.

Janout et al. (2010) reported similar anomalies in 2006–2008 for shelf waters in the northern Gulf of Alaska, based on observations from oceanographic station GAK1 (located at the mouth of Resurrection Bay near Seward, Alaska, at approximately 60°N, 149°W). GAK1 is approximately 750 km WNW of Glacier Bay and is approximately 270 m deep (similar to Glacier Bay Station 04); GAK1 has recorded the longest time series (40 years) of coastal temperature and salinity in Alaska. The University of Alaska Fairbanks School of Fisheries and Ocean Sciences, Institute of Marine Science maintains the GAK1 time series website (<http://www.ims.uaf.edu/gak1>) that shows the 2006–2008 cold anomalous pattern extending into late 2009 (http://www.ims.uaf.edu/gak1/Plots/GAK1_Anomaly_250.png). Janout et al. (2010) attribute the recent cooling and increased salinities in the northern Gulf of Alaska to a complex set of ocean-atmosphere interactions primarily driven by dynamics of the Aleutian Low pressure center that dominates meteorological conditions in the gulf during fall and winter and modulates ocean-atmosphere heat flux. The recent period of anomalously cold waters appears to have been

influenced by winters of relatively cold, dry continental air accompanied by relatively little freshwater discharge in the fall and winter months. Strong winter wind mixing and surface heat loss are not enough on their own to generate deep cold anomalies. However, when strong winds and large ocean-to-atmosphere heat fluxes are accompanied by relatively low levels of salinity stratification (induced by low runoff conditions) the cold signal can propagate across the entire coastal water column (Janout et al. 2010). While we have not undertaken a similar heat flux balance for the Glacier Bay stations, we expect that similar conditions were present in southeastern Alaska where effects of the Aleutian Low are also keenly felt in winter.

Etherington et al. (2007) and Sharman (2010) have described a generalized model for Glacier Bay oceanography and marine production that is typified by strong seasonality and high productivity. The winter condition is characterized by vertically well-mixed waters that are presumably nutrient-rich but supportive of very low primary productivity because of limited light (short day length) and weak to non-existent physical stratification of the water column. With the onset of spring, warming temperatures and increasing input of fresh water (primarily from melting snow and glacial ice), a near-surface stratified layer is established which in the presence of increasing day lengths allows for bloom conditions and the beginning of a sustained period of primary productivity. Stratification further strengthens into the summer, but phytoplankters do not deplete nutrients in the photic zone (and suffer a “bloom crash”) everywhere because Glacier Bay’s strong tidal currents and/or possibly wind-driven upwelling continue to inject nutrients from depth – in at least some “hotspot” locations. This fine balance of maintaining near-surface stratification in the presence of just enough mixing to replenish nutrients for phytoplankton growth is the key to Glacier Bay’s overall productivity. In the fall, a combination of decreasing day length and temperatures, and possibly strong storm activity that may assist with a breakdown of surface stratification, all contribute to a decline in primary productivity that ultimately develops into the dark, well-mixed, biologically constrained winter condition.

The 2009 patterns of increasing temperature and salinity with distance along transect from the heads of the inlets conforms to prior expectations. One expects the upper fjords to be sources of high freshwater input from melting snow and ice, including tidewater glaciers and turbid outwash streams. At the same time, the lower/central bay is closer and more integrally connected to the warmer, more saline oceanic waters of the Gulf of Alaska. It is interesting that mean temperatures across the upper 50 m of the water column increased from March until at least October for four of the seven core stations. The three exceptions, all in the main trunk of Glacier Bay, peaked in late summer and then began cooling, suggesting that lower bay waters respond more quickly to seasonal cooling of ambient air temperatures (which peak in mid- to late summer). A reasonable interpretation is that shallower stations in the lower/central bay, closer to the shallow entrance sill, experience greater tidal mixing, thereby efficiently coupling heat fluxes between surface waters and the atmosphere. Additionally, stations in the northern reaches of the fjord are more protected and subsequently experience a lesser degree of wind mixing. The decline in salinity throughout the water column after spring/early summer likely reflects the influence of increasing freshwater input as air temperatures warm and snowmelt proceeds. The ranges of both temperature and salinity values were relatively cool and fresh, respectively, compared to open ocean conditions; they also varied seasonally more than oceanic waters (see <http://www.pmel.noaa.gov/ocs/disdeld/disdeld.html> for time series data from Ocean Station P, 50°N, 145°W). Both of these patterns reflect responsiveness to local coastal conditions, spatially buffered from the open ocean.

The relatively shallow pycnocline depth, generally 2–50 m, provides a physical discontinuity within the photic zone at most stations for much of the year. This density stratification helps keep phytoplankters in the sunlit surface portion of the water column where they can grow and reproduce rapidly. Strong pycnoclines can also hamper nutrient renewal from depth, which is required for phytoplankton blooms to be sustained as the plants strip out available nutrients. However, in Glacier Bay it is apparent that physical forces (perhaps tidal mixing) or other processes provide for nutrient replenishment throughout the spring and summer (Etherington et al. 2007). This is reflected in the 2009 fluorescence patterns across the seasons. Although the data were available only starting in April and were variable both spatially and temporally, the mean chlorophyll-*a* values of 8–18 mg/m³ indicate relatively high and sustained primary productivity (Mann and Lazier 2006). Patterns of dissolved oxygen concentration generally agree with what should be expected given the patterns of biological productivity. Near-surface peaks in June followed by slight declines suggest initial plant growth (production via photosynthesis) followed by consumption (decomposition of organic matter). Nevertheless, mean concentration ranges of 4–7 ml/L throughout the water column (at least starting in June when data became available) clearly indicate that deep water renewal occurs, preventing anoxic conditions throughout the measured water column. Although dissolved oxygen data is lacking for early spring 2009, the June oxygen concentration peak in the bottom water may indicate an April/May renewal timeframe. 2010 data will be examined for this pattern.

The increase of turbidity until mid-summer with a subsequent decrease aligns with the likely rate of turbid freshwater discharge into the upper inlets, along with high phytoplankton densities through the summer. It comes as no surprise that the highest turbidity measurements (and lowest PAR measurements) were generally observed at the extreme heads of the inlets.

Perhaps the most biologically important parameter currently measured in the oceanographic monitoring program is fluorescence, a proxy for phytoplankton standing stock. In order to properly calibrate the fluorometer, water samples must be collected, filtered, and then regressed against the fluorescence profile. Lack of data on nutrient availability remains an important constraint to improving our understanding of the proposed generalized model for Glacier Bay oceanography and marine productivity. This parameter, too, requires analyses of field water samples. Both of these—direct chlorophyll and nutrient measures—are elements in a GLBA/SEAN ocean acidification study that will begin in July 2011 and run for three years.

Recommendations

Water sampling—scheduled to begin in 2011—is for the reasons stated above a very positive addition to the monitoring program. Similarly, the 2010 procurement of a dedicated SEAN vessel designed to accommodate oceanographic monitoring, available on a priority basis for surveys, and able to be operated by multiple personnel, will all enhance the amount and quality of data collected.

Cast depth is a parameter deserving of additional consideration. On some days at some stations wind and/or current can cause the vessel to drift during the cast. This creates line angle between the surface and the CTD, making for a cast that may be significantly shallower than the target depth (currently based solely on the length of line cast over the side). In some cases this can also mean that the target “standard oceanographic depth” determined to represent “bottom water” for a given station may not be reached by the CTD. In 2009 this was the case for Stations 01 and 07 in August, for example. If this continues to be a problem we should consider remedies such as increasing the length of line over the side to make up for line angle, initiating the cast upwind/current of the station location and carefully motoring the vessel with the wind/current during the cast to reduce line angle, or some combination.

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